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OCEANOGRAPHY.—*An instrument for accurate and rapid density measurements on board ship.*[1] A. L. THURAS, Bureau of Standards. (Communicated by S. W. Stratton.)

The ordinary hydrometer has long been discarded for accurate oceanographic work because of the irregularities and variations in its indications. Almost all of these errors are to be found at the surface of the liquid measured, as for instance, changes in surface tension, impurities on the surface influencing the shape of the meniscus on the stem of the hydrometer, and irregularities in the wetting of the stem. These errors are all eliminated in the float, or bobbin, of total immersion. Therefore this method has been investigated and studied with the hope of possibly improving and simplifying it, so that rapid and accurate density measurements can be made on board ship.

The method was probably first suggested by Pisati and described in 1890 by Reggianni, who used hydrometers of total immersion on board the *Washington* of the Royal Italian Navy in the Mediterranean in 1883. He used two modifications, one consisting of a hydrometer of constant specific gravity and the other consisting of a hydrometer of variable specific gravity. In the first modification, equilibrium in weight of the hydrometer and solution was effected by adding measured quantities of distilled water to the solution; in the second modification equilibrium was

[1] Done under the auspices of the Interdepartmental Committee on Oceanography, subcommittee on instruments, apparatus, and measurements.

attained by adding weights to the hydrometer. Reggianni did not determine the specific gravity of the sea water beyond the fourth place of decimals.

Dr. Nansen in 1896, while studying the salinity of the North Polar Basin, developed a method similar to the second modification of that of Pisati and Reggianni. A hydrometer of total immersion, 3.5 cm. in diameter and 15 cm. long, of normal Jena glass No. 16^{III} was used. The observations were made in a Dewar cylinder, and equilibrium was attained by adding platinum weights to the float, the final adjustments being made by slightly varying the temperature of the sample until the density of the liquid was exactly equal to the density of the float. The temperature of the sample was carefully measured by three thermometers, the bulbs of which were placed in the upper, middle, and lower strata of the sample. An accuracy of one in the fifth decimal place was attained. Dr. Nansen makes the following remarks in regard to this method:

> It is most astonishing that so little attention has hitherto been paid by oceanographers to this valuable method. . . . . After a little practice I think that the method of those observations might be so arranged that they should not take much more time than ordinary determinations with the hydrometer, if the latter were to be made fairly accurate. In my opinion, the method promises to become important for future oceanographic work, as it should enable us to determine the density and salinity of the ocean with a considerably higher degree of accuracy than has hitherto been reached. And it excludes, even in the case of less skillful investigators, the chief source of error, vitiating, under ordinary circumstances, all observations made with the common hydrometer.

T. W. Richards has also made a careful study of this method and has obtained a much higher degree of accuracy. The solution to be investigated is placed in a liter Erlenmeyer flask immersed in an adequately stirred bath in which the temperature can be kept constant to 0°.001 C. He was able to measure densities to a few units in the seventh decimal place.

A. B. Lamb and R. E. Lee have also attained very high accuracies by using an electromagnetic attraction to obtain the equilibrium condition. A piece of soft iron is enclosed in the bulb of the sinker and by means of an electric current sent

through a properly placed external circuit, an electromagnetic attraction is exerted in a vertical direction on the bulb. The utmost precautions had to be taken to maintain a constant accurately known temperature, to avoid any jarring of the apparatus, and to avoid errors due to eddy currents in the liquid.

In all of these modifications of the total immersion method of measuring the density of liquids, the outstanding difficulty is the production of small and accurately known variations in the bouyancy of the sinker. Some easily variable, easily measurable force that will produce vertical displacements of the bobbin is wanted.

Such a force can most conveniently and easily be obtained indirectly by varying the temperature of the liquid. This method is employed in the apparatus that is described below. Numerous analyses having shown that the composition of sea-water salts is very nearly the same in all parts of the ocean and at all depths, the concentration alone changing, the temperature coefficient of expansion of all samples will be the same and the constant of the apparatus will need be determined but once for all.

The maximum variation in the density of the sea water in the open ocean is less than one per cent, so that the density of the most saline water can be made equal to the density of the least saline water by raising its temperature 20°C. Also, the coefficient of expansion of sea water is so low that a sufficient degree of accuracy in the density can be obtained without an excessively close reading of the temperatures. This method also eliminates measurements other than that of temperature, which is always needed in accurate density determinations.

The apparatus (fig. 1) consists essentially of a test tube containing the float, or bobbin, and the liquid to be measured, a stirred variable temperature bath, and an accurately calibrated thermometer.

The bobbins are made of Jena glass No. 16^{III} about 5 cm. long and 12 mm. in diameter. They were carefully annealed about eight months ago and have probably settled down to a definite volume. The glass test tube to contain the liquid to be meas-

ured is 18 mm. in diameter and 15 cm. long, and requires from 15 to 30 cc. of the liquid to be tested.

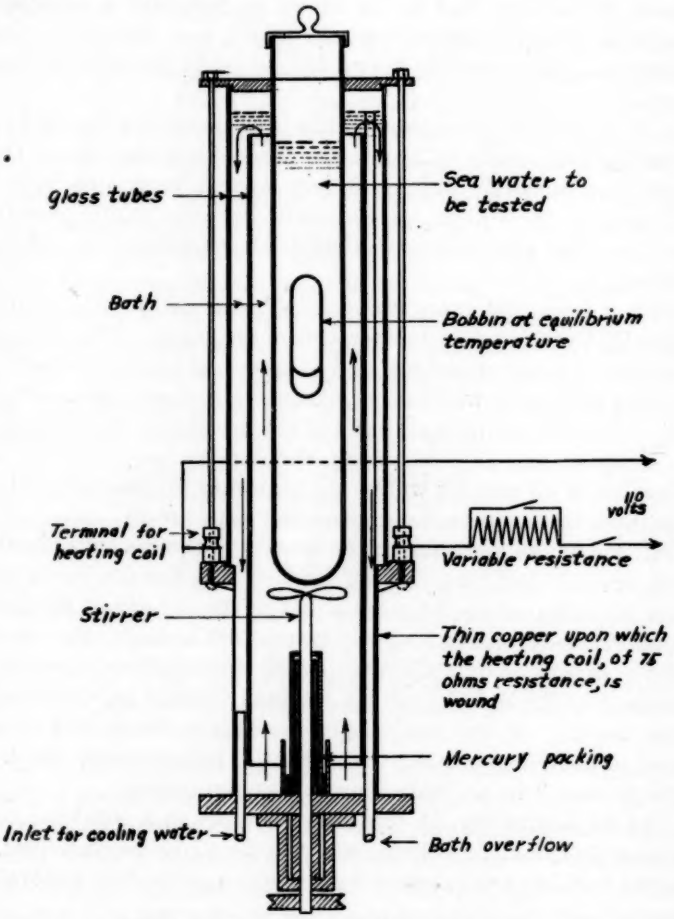

Fig. 1. Apparatus for density determinations.

The temperature bath is of copper and glass and is made as small as possible; it holds only 270 cc. of water. The lower part of the bath is made of 0.3 mm. copper, on the outside of

which is wound 75 ohms of "advance" resistance ribbon, whereby the bath can be rapidly heated electrically. The base contains a stirrer and inlet and outlet tubes for cooling water. The upper part of the bath is made of ordinary glass tubing and contains a copper cover through which a thermometer and the test tube containing the liquid can be inserted.

A standard stem type thermometer graduated in 0°1 is secured in the cover of the bath with its bulb immersed in the liquid of the bath. The temperatures can easily be read to 0.1 of a division.

The method of making a determination depends on noting the precise temperature at which the liquid to be tested is exactly of the same density as the bobbin. It is apparent that this point, where the bobbin neither sinks nor rises, must occur in a particular liquid at a perfectly definite temperature. In an actual test this equilibrium temperature is not obtained, but pairs of readings approaching it from a higher and from a lower temperature are successively made until a pair is obtained covering such a small range of temperature that their mean may be regarded as sufficiently close to the equilibrium temperature to give the required accuracy in density. The temperature coefficient of sea water is such that a sufficient degree of accuracy can be obtained by determining this equilibrium temperature to 0°05 C. The rapidity in reaching these points depends on the viscosity of the water and, consequently, increases with the temperature. This in some measure compensates for the decreased sensitivity caused by the increased temperature coefficient at higher temperatures. Therefore a high degree of accuracy in a limited time is not necessarily obtained by cooling the sea water to such a temperature that the coefficient of expansion is small. Consequently that part of the temperature-density curve of sea water which is most convenient to work with has been selected in the present work, and the bobbins have been made of such a density that all of the equilibrium temperatures come between room temperature and about 40°C.

In building this density apparatus the requirements for use at sea have been constantly kept in mind. The essential

requirements are simplicity and convenience of operation, freedom from disturbances due to the motion of the ship, rapidity, accuracy, and limitation in the quantity of test water used.

The apparatus is simple and rugged. All of the glass parts except the thermometer and bobbin are stock articles, and the bath is so constructed that it can easily be replaced if broken. The heating and cooling elements and the stirrer are contained in the copper base and are protected so that they can not easily be injured. The operation of the bath is simple and convenient. The test tube containing the liquid and bobbin is placed in the bath and, by means of the heating coil and cooling tubes the temperature is varied until the equilibrium point is reached. The only readings necessary are the temperatures of the bath for the final two movements of the bobbin.

An instrument that is to be used on board ship should operate rapidly. The bath and test tube containing the sample were therefore made as small as possible, the heating coil was placed close to the liquid of the bath and the cooling water was passed directly into the liquid. With full voltage on the heating coil the bath can be heated 10° in less than two minutes, and can be regulated by an external resistance to 0°01. The test tube containing the sample is 18 mm. in diameter and has such a small temperature lag that under ordinary circumstances a single test can be made in less than ten minutes.

The accuracy in density determinations demanded in oceanographic work is 1 or 2 units in the fifth decimal place; this requires that the equilibrium temperature be read to 0°05 C. In figure 2 are shown for each of four bobbins the curve connecting the equilibrium temperature and the salinity and density of the sea water in which it is immersed. Repeated tests on the same sample over several days gave consistent results, and no two tests of the equilibrium temperature had as large a difference as 0°05.

From some subsurface samples only a limited quantity of the water can be used, as most of the sample is required for biological purposes. With this apparatus 30 cc. is sufficient for a test, and with a little more difficulty a test can be made with only 15 cc.

The only constant error is that due to a permanent change in the volume of the bobbin. To reduce this error the bobbins were constructed with great care. They are made of normal Jena glass No. 16^{III} and were carefully annealed about eight months ago. There has not been sufficient time to determine their change in volume due to aging, but it is believed that they have now attained a volume that is constant enough not to affect appreciably the measurements of density. T. W. Richards has

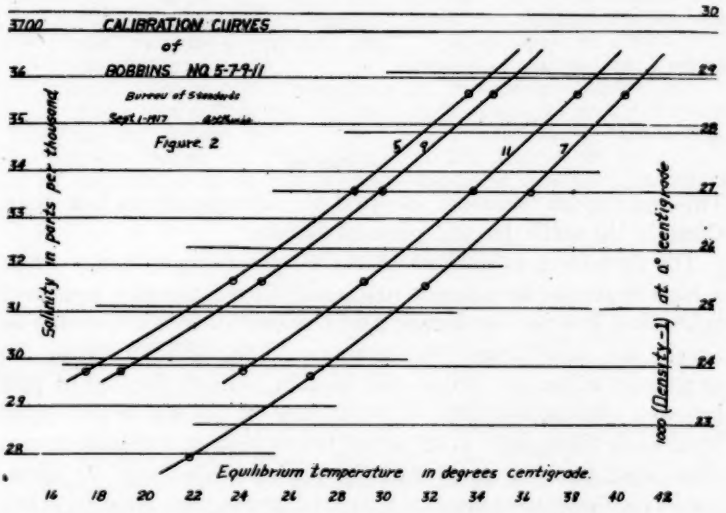

Fig. 2. Relation between equilibrium temperature and density and salinity.

examined carefully the effect of aging, using various kinds of glass, and finds that after three or four months the change in volume of the glass is exceedingly small.

To determine the error due to sudden heating and cooling, the bobbin and liquid were placed in a sealed glass tube and the following results were obtained, using a Beckman thermometer to measure temperatures:

	Equil. temp.
From room temperature	20.74
After being in a bath of 56°C. for 10 minutes	20.75
After being in an ice bath for 10 minutes	20.755
After being in a bath of 80° for 20 minutes	20.75

The changes in density corresponding to these changes in temperature are negligible.

To determine the rapidity and reliability of the method, a series of tests were made on the same sample of water, no single test taking longer than ten minutes. The following results were obtained using a new sample in the test tube for each measurement:

Sample No.	*Equil. temp.*
1	28.40
2	28.38
3	28.39
4	28.38
5	28.40
6	28.39
Mean	28.39

This maximum variation of 0°01 C. corresponds to less than three in the sixth decimal place of density.

The formation of bubbles on the bobbin is troublesome when a high degree of accuracy is required. It is fortunate, however, that when bubbles are forming on the bobbin it is impossible to obtain an equilibrium temperature. This difficulty may be overcome either by lifting the bobbin out of the liquid just before a reading is taken, or by driving off the air in the liquid by heating the sample to 50° or 60° before making a measurement. The latter method was found the more satisfactory. It eliminated the difficulty completely, but, of course, care must be taken to avoid evaporation.

Conclusion. A simple apparatus is described by which the density of sea water can be measured on board ship with speed and precision. With carefully calibrated bobbins a density measurement of a liquid of known temperature coefficient can be made in less than ten minutes to an accuracy of more than two in the fifth decimal place. The particular advantage of the method lies in the facts that (1) by changing the temperature of the liquid its density can easily and quickly be brought exactly to the density of the bobbin, and (2) at equilibrium temperature the sensitivity of the method is unaffected by the motion of the vessel, the liquid and bobbin having the same density.

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